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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

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WITH A
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by

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An Optical Study of Ammonium Perchlorate Sandwiches with a Polybutadiene Acrylic Acid Binder

by

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ABSTRACT

Ammonium perchlorate/polybutadiene acrylic acid propellant sandwiches were burned in a nitrogen purge atmosphere at various pressures in a combustion bomb designed for optical and rapid de-pressurization studies. A Hycam camera was utilized for taking high speed color schlieren and regular photographs to obtain information about the flame structure during combustion. The effects of pressure on flame structure are discussed.

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ACKNOWLEDGEMENT

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I. INTRODUCTION

Ammonium perchlorate (AP) has been used in solid rocket propellants for a long time, and as a result has been subjected to a great deal of study.[1] However, the actual physical processes that exist when AP burns as an oxidizer in a solid propellant rocket are not well understood. A consequence of the lack of understanding is that the grain design of a solid propellant rocket proceeds based on subscale empirical data and certain theories[2] which are useful as starting points.

Many models have been proposed for the combustion of composite propellants. For example, Summerfield's diffusion flame model [4], where the rate of chemical reaction between fuel and oxidizer in a diffusional process is said to be controlling (see Fig. 1); the two stage granular diffusion flame model by Summerfield and Steinz [5], used for extending the applicability of the diffusion flame theory to lower pressure (see Fig. 2); Fenn's phalanx flame model [6], which has the addition of a premix region at the base of the flame and no longer considers the surface essentially planar at anything other than at low pressure (see Fig. 3); the model by Hermance [7], which accepts and treats the fact of surface heterogeneity but assumes heterogeneous reactions between fuel and oxidizer in presupposed fissures surrounding

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[1]Reference 1 is a survey on ammonium perchlorate combustion and decomposition, containing over 400 references. Ref. 2 is a survey on AP composite combustion and lists over 300 references.

[2]Some of the assumptions made in modeling composite propellant combustion are discussed in a recent paper by Boggs [3], in respect to their compatability with what is known experimentally.

the oxidizer particles (contrary to present experimental evidence), (see Fig. 4), (this model was later modified to include diffusional mixing [8]); the multiple flame model of Beckstead, et al. [9], which is based on a flame structure around individual crystals of oxidizer and considers three separate flame zones, (see Fig. 5); and other models [10-14]. The most recent model for AP combustion, due to Guirao and Williams [15], is based on exothermic reactions occuring in a liquid layer and "equilibrium dissociative vaporization" followed by gas-phase combustion for AP not consumed in the liquid-phase reaction. This model should be most useful since recent experimental evidence for a liquid layer is incorporated and the model requires only one empirical constant for a close fit of experimental data over a wide range of pressure.

The above models are based on many different proposed physical phenomena and no general agreement has been reached concering which of the models most nearly agrees with the actual burning mechanism(s). Recent studies have been conducted utilizing propellant sandwiches. These two-dimensional propellants allow the binder/AP interactions to be studied over a wide variety of test conditions and propellant ingredients. However, the direct application of sandwich propellant results to actual propellant behavior remains in question.

While the combustion process of a modern rocket is only part of the overall system, it is impossible to design a grain without having to perform a great deal of experimental analysis to insure its proper operation. The temperature sensitivity of propellant regression rate, the effects of ballistics modifiers (burning rate catalysts, etc.), the effect of AP crystal size, etc. cannot be adequately understood and

utilized to design advantage if the basic combustion process is not understood. For these reasons, many basic studies of solid propellant combustion are still being conducted.

II. OBJECTIVES AND METHODS OF INVESTIGATION

This investigation had two specific objectives. The first was to see if additional experimental evidence regarding the existence of a liquid layer (melt) on the surface of pyrolizing AP could be obtained. In several papers on the deflagration of AP where combustion was extinguished by rapid depressurization, scanning electron microscope (SEM) studies [16-24] of the extinguished surface have provided very strong evidence for the presence of a melt.

The second objective was to try to simulate on a large two-dimensional scale the interface between the ammonium perchlorate and binder of a simple composite propellant in order to gain visual information about how it burns in various environments (i.e. whether the type of flame is laminar, turbulent, premixed, diffusive, or a combination of some or all). The type of flame(s) which exist and the existence of a liquid AP melt have a dominant role in any combustion modeling.

Several motion picture and extinguishment studies of sandwich burners have been conducted [23-25]. These studies have visually depicted the effects of various operating conditions (such as pressure, type catalyst, and amount of catalyst present) on the burning surface and flame configurations. However, in order to gain additional information on the flame structure it is necessary to use a technique which will give information on density or temperature variations in the flame. In addition, the deflagration of AP is not visible at nominal pressures ($<$1000psi). Any interaction of the AP deflagration or decomposition

products with the visible flame is not directly obtained by visual observation. Therefore, a combustion bomb was designed and fabricated which could be utilized for various optical studies (schlieren, interferometry and holograms) of burning propellants.

Pressed AP crystals with a PBAA binder were used in this study. It is pertinent at this point to note that the pressed AP crystals which were used in this study (composed in this case of granulated 200 micron particles) had densities and burning rates very close to grown crystals at substantially less expenditure of time and money in procurement. SEM photographs of unburned pressed crystals [26] showed that (for ultra high purity AP) the AP was closely compacted with very few voids. In addition to the economic advantages of using pressed crystals, they also provide the opportunity for study of the effects of various impurities and additives simply by incorporating them into the AP or binder.

III. DESCRIPTION OF APPARATUS

A stainless steel combustion bomb was designed and fabricated for an operating pressure capability of 0 to 1000 psi, and hydrostatically tested to 1500 psi. It was composed of three main sections — base, center (or window), and exhaust. Integral provision was made for mounting AP sandwiches and a N_2 purge system. Figures 6 to 17 are photographs of the combustion bomb. Figure 18 is a schematic showing principle dimensions of the assembled bomb. Figure 19 is a schematic showing the angular relationship of the windows in the combustion bomb. Figure 20 is an electrical schematic of the control panel, with Figure 21 showing panel location behind the safety shield. The exhaust section (see Figs. 11, 12, and 17) was designed for the later addition of a bolt-on rupture diaphragm for rapid de-pressurization studies.

One inch diameter compressed AP discs were made for use in the propellant sandwiches as outlined in Ref. 24 except as noted below. Table I is the data summary of one inch pressed crystals from which the propellant sandwiches used in this study (and a simultaneous study in the NPS photographic centrifuge) were made. All the one inch pressed crystals were made at a pressure of 30,500 lb/in^2. The ten minute grind time used by Varney [24] was eliminated, and compaction time was reduced to twenty minutes when it was found that the changes did not have any noticeable effect on the burning rate or the disc specific gravity. Figure 22 is an exploded view photograph of the one inch compaction mold used in making the pressed crystals.

Table II is the data summary for the PBAA binders used in propellant sandwich formulation. Figure 23 is a schematic of the optics for the

one dimensional schlieren. Details of schlieren methods are presented in Refs. 27 through 33. Figure 24 is a schematic of the optics for the two dimensional schlieren (see Refs. 34 and 35 for theory and/or apparatus construction).

Figure 25 is a photograph of the two-dimensional knife edge, showing the adjustable knife edges for aperture control. Figure 26 shows the location of the knife edge on interconnected translation stages capable of giving precision movement in the vertical, horizontal, and lateral directions.

For the schlieren work, a model K2004E-115 Hycam camera with variable framing rates from 1000 to 10,000 frames/sec., and a pulse timer were utilized. The light source for the one-dimensional schlieren was a mercury arc lamp. The two-dimensional schlieren used a modified Spindler and Sauppe Inc. slide projector (SLM-1200) as a light source.

The components used in both the one-dimensional and two-dimensional schlieren systems were aligned with an Optics Technology Inc. He-Ne laser, in order to insure minimum distortion.

The SLM-1200 projector (1200 watts) and a television flood light (625 watts) were used as listed in Table III for side illumination of the propellant sandwiches.

IV. EXPERIMENTAL PROCEDURE

Ammonium perchlorate sandwiches were prepared by binding AP crystals with PBAA. The AP faces were separated by .001 inch shim stock during cure which provided a uniform binder thickness. The choice of .001 inch (approximately 25 microns) was a result of calculations involving AP/binder loading and considerations of maximum or minimum surface to volume geometrical arrangements of AP in a binder of a composite AP propellant. After curing, the large sandwiches were cleaved into small sandwiches. The small sandwiches were 0.15 inches (depth in optical path) by approximately 0.35 inches high.

The samples were mounted in the combustion bomb and ignited with a nichrome resistance wire. The schlieren, or optic image was focused directly on the camera film plane in all cases.

Tests were run in several configurations, listed in Table III. The neutral density filters and the primary mercury vapor line filters were used to attempt (unsuccessfully) differentiation between flame light and schlieren effect in the one-dimensional (black and white) films.

V. RESULTS

As a preliminary to what was observed, a brief summary of some results already obtained for AP sandwiches with PBAA binder [24,25,36] is presented:

1. Melted PBAA flows over some of the AP, the amount of AP covered by binder melt being dependent on pressure.
2. The binder-oxidizer interface is smooth, i.e., there are no significant interfacial reactions.
3. The maximum surface regression occurs in the AP in the pressure range from AP deflagration limit (approximately 280 psi) to 1000 psi.
4. At a binder thickness somewhere below 50 microns a "hump of AP" (covered with molten binder) can occur and gives asymmetrical burning [36]. This effect was not so predominant in Varney's work [24].
5. A liquid layer is present on the AP during combustion at pressures above the lower deflagration limit.

As may be noted from the listing of Table III (runs were not listed when they were of no value as a result of no ignition, delayed ignition, film ruined in development, etc.) the usual learning process occured, and those runs listed up to film number 29 are simply to show some of the variations which were attempted. Film numbers 29 through 31 gave pictures which were difficult to interpret due to the mixing of the four schlieren colors with the flame light. Little could be determined except that the gradients in the vertical direction were very weak at 500 psi.

With the change from a solid knife edge to the blue/red filter matrix and changing the camera focusing lens, the light available for film exposure increased by a factor of about 20 (object to image ratio from 1:1 to 3:1 and no loss at the knife edge) with no decrease in sensitivity.

Figure 27 is a photograph taken at 800 psi from film number 44. Three things in particular are of note. The exposed binder has a large height (which results from the high rate of AP deflagration at 800 psi) and the flame color (both the primary flame coming from the surface and that on the binder) is yellow. The orange colors coming off of the binder at lower pressures (discussed below) are absent. Finally, a large amount of visible smoke is present.

Figure 28 is a color schlieren taken at 800 psi from film number 39. It may be characterized by the gross turbulence visible at heights above the primary flame, a general darkening of colors from AP smoke interaction, and the long dark center area from the exposed binder. Particularly interesting are the light green, orange, and orange-reds in the primary flame on both sides of the binder.

Figure 29 is a photograph taken at 500 psi from film number 42. Binder protrusion above the pyrolizing AP is less than at 800 psi. There is also less visible smoke from the AP than at 800 psi. The appearance of a large amount of orange in the binder flame and a lesser amount being present in the primary flame means that a red schlieren color shift interacting with yellow flame light can no longer be positively distinguished.

Figure 30 is a schlieren taken at 500 psi. Turbulence, while still severe, has decreased. In Fig. 30 the presence of light green color

along the side of the primary flame is of primary importance since the oranges present could be from flame light. The only way to obtain the green is from a blue schlieren light shift interacting with the yellow flame.

Figure 31 is a photograph from film number 45. The pressure was 200 psi which is below the lower pressure deflagration limit (PDL) for AP burning as a monopropellant. The primary flame is wider than at higher pressures and the binder flame is much shorter. The AP which has not burned or sublimed protrudes above and slopes away from the flame zone.

Figure 32 is a schlieren taken at 200 psi and is markedly different from those taken at 500 and 800 psi. Gas flow above the sandwich is essentially laminar with some mixing with the N_2 purge gas. No green is visible along the primary flame. Dark regions exist on each side above the decomposing AP.

Figure 33 is a photograph from film number 46 taken at 50 psi. It is similar to Fig. 31 except that the ability to distinguish between a primary flame and a binder flame has been lost, and the area encompassed by the flame (both height and width) is reduced.

Figure 34 is a schlieren from film number 43 taken at 50 psi. The gas flow is quite laminar and again the absence of any green in the flame may be noted. The dark regions observed at 200 psi are more dominant.

Figure 35 is a photograph taken at 500 psi from film number 47. It is different from the other photographs (schlieren and non-schlieren) in that the sandwich faces are no longer parallel to the optical axis of the schlieren system. The purpose of having the angled orientation was

to give a representation of the averaging effects that must be considered in any interpretation of Figs. 27-34. Sandwich height varied from .3 to .45 inches but a special emphasis was placed on consistency of width (.15 inches) in order to avoid having to consider different averaging effects at the various pressures used.

VI. CONCLUSIONS AND RECOMMENDATIONS

At 500 and 800 psi there is evidence (green color resulting from the blue schlieren light shift and the bright yellow flame) of a very low density area along the side of the primary flame. This indicates the presence of a diffusion flame at the area of maximum heat release. The gases evolving from the surface (both from the primary flame and the deflagrating AP) are visibly turbulent.

The lack of any green in the schlieren picture at 200 and 50 psi indicates that a change in the burning process has occured or that the area of heat releases is too close to the surface for resolution (estimated to be about 25 microns when projected on a screen). The schlieren pictures at 50 and 200 psi are what one would expect for a premixed laminar flame. Unfortunately, schlieren pictures for vertical flame gradients were not taken at 50 or 200 psi. The gases evolving from the surface (including the AP decomposition) are visibly laminar. The dark regions which exist on either side of the primary flame above the AP are thought to result from the opaque AP decomposition gases.

The significant differences in the results obtained at high and low pressures are presumed to result from operation above and below the lower deflagration limit of AP. Schlieren films taken just above and below the PDL will be required to clarify this behavior.

It should also be mentioned that the "fingerlike flamelets" noted by Boggs [23], for carboxyl terminated polybutadiene, hydroxyl terminated polybutadiene and polyurethane binders was present for the polybutadiene acrylic acid binder used in this investigation (Fig. 35).

Either laser schlieren or laser interferometry pictures would eliminate any possibility of flame light interaction through the use of suitable filters and should be taken for substantiating the above conclusions.

Finally, it is concluded that, of those models available for composite solid propellant combustion, the one which is most descriptive of what was observed in this study of AP/PBAA sandwich combustion is the multiple flame model by Beckstead, et al. [9].

The color schlieren technique used in this investigation provides a valuable additional method for the study of solid propellant sandwich combustion. Future studies should include (a) deflagration of pure AP as a function of pressure (originally intended to be conducted in this investigation), (b) the effect of binder thickness and composition on flame structure, and (c) the effects of additives or impurities in ammonium perchlorate monopropellant deflagration.

TABLE I

AP DISK DATA SUMMARY

No.	Wt. (gm)	Thickness (in)	Density (gm/cm^2)	Ratio to Single Crystal AP Density
1	1.278	.052	1.92	.98
2	1.276	.051	1.93	.99
3	1.289	.052	1.91	.98
4	1.234	.052	1.85	.95
5	1.271	.052	1.90	.97
6	1.267	.053	1.83	.94
8	1.281	.053	1.89	.97
9	1.279	.053	1.87	.96
10	1.272	.053	1.88	.96
11	1.278	.052	1.89	.97
12	1.248	.052	1.87	.96
13	1.268	.052	1.88	.96
14	-	.053	-	-
15	1.267	.052	1.88	.96
29	1.288	.052	1.89	.97
31	1.297	.053	1.89	.97
33	1.297	.052	1.89	.97
35	1.297	.052	1.92	.98
66	1.308	.053	1.92	.98
67	1.317	.053	1.92	.98
68	1.310	.053	1.93	.99
69	1.324	.053	1.93	.99
70	1.313	.053	1.92	.98
71	1.311	.053	1.94	.99
72	1.310	.052	1.94	.99
74	1.310	.055	1.85	.95
90	1.308	.053	1.92	.98
91	1.301	.052	1.94	.99
92	1.311	.053	1.94	.99
93	1.299	.052	1.92	.98
94	1.307	.053	1.92	.98

TABLE I (Continued)

No.	Wt. (gm)	Thickness (in)	Density (gm/cm^2)	Ratio to Single Crystal AP Density
95	1.306	.053	1.92	.98
96	1.306	.053	1.93	.99
97	1.305	.052	1.94	.99
98	1.306	.053	1.91	.98
99	1.314	.053	1.93	.99
100	1.311	.052	1.94	.99
101	1.306	.052	1.94	.99
102	1.310	.052	1.94	.99
105	1.310	.053	1.91	.98
106	1.307	.052	1.94	.99
107	1.310	.052	1.94	.99
108	1.311	.052	1.94	.99
110	1.301	.052	1.93	.99
111	1.307	.052	1.94	.99
112	1.303	.052	1.93	.99
113	1.302	.053	1.92	.98
114	1.301	.053	1.90	.97
115	1.300	.052	1.94	.99
116	1.306	.052	1.94	.99

Note: Use of the 10 minute grind time and 24 hour press time was eliminated after No. 15.

TABLE II

PBAA BINDER DATA

Batch No.	PBAA (gm)	EPON 828 (gm)	Cure time* (hrs)	Used on Crystals Nos.**
1	.854	.159	72	1, 2, 3
2	3.203	.613	73	10, 11, 12, 13, 14, 15
3	3.203	.614	80	4, 5, 6, 7, 8, 9
4	3.202	.613	73	31/35, 29/33
5	3.202	.613	77	66/67, 68/69, 70/71, 72/74
6	3.203	.613	83	90/91, 92/93
7	3.201	.614	72	96/97, 98/99, 100/101
8	3.203	.614	72	95/105, 106/108, 107/109, 114/115, 112/113

*Temperature on all cures was 72°C.

**Prior to Batch No. 4 pressed crystals were first cleaved to make sandwich faces, after which binder was applied. Subsequent to batch No. 4 shim stock was used to separate two different pressed crystals during cure. After curing, the large sandwich was cleaved into the desired size.

TABLE III

EXPERIMENTAL RUN DATA

Film No.	Light Source	Film Type[1]	Camera Shutter	Framing Rate	Focusing Lens	Filter	External Lighting	Knife Edge	Pressure
4	Hg	Color	1/2.5	4×10^3	609.6 mm, f6	None	None	Hor.	500
6	Hg	Color	1/2.5	4×10^3	609.6 mm, f6	Kodak #38A	None	Hor.	500
8	Hg	Color	1/2.5	4×10^3	609.6 mm, f6	None	Photo Flood @90°	Hor.	500
10	Hg	Color	1/2.5	10^4	609.6 mm, f6	Kodak #38A	Photo Flood @90°	Hor.	500
11	Hg	B&W	1/2.5	10^4	609.6 mm, f6	None	Photo Flood @90°	Hor.	500
12	Hg	B&W	1/2.5	10^4	609.6 mm, f6	.3NDF	Photo Flood @90°	Hor.	500
13	Hg	B&W	1/100	10^4	609.6 mm, f6	None	Photo Flood @90°	Hor.	500
16	Hg	B&W	1/100	10^4	609.6 mm, f6	.3NDF	Photo Flood @90°	None	500
17	Hg	B&W	1/100	10^4	609.6 mm, f6	5641A	Photo Flood @90°	Hor.	500
19	Hg	B&W	1/100	10^4	609.6 mm, f6	5641A	Photo Flood @90°	Hor.	500
20	Hg	B&W	1/100	10^4	609.6 mm, f6	5641A	None	Vert.	500
22	Hg	B&W	1/100	10^4	609.6 mm, f6	None	SLM @90°	Vert.	500
25	SLM	Color	1/100	10^4	609.6 mm, f6	None	None	2-D	500
27	SLM	Color	1/2.5	20×10^2	609.6 mm, f6	None	None	None	500
29	SLM	Color	1/2.5	20×10^2	609.6 mm, f6	None	Photo Flood @90°	2-D	500

TABLE III (Continued)

Film No.	Light Source	Film Type	Camera Shutter	Framing Rate	Focusing Lens	Filter	External Lighting	Knife Edge	Pressure
30	SLM	Color	1/2.5	25×10^2	609.6 mm, f6	None	Photo Flood @45°	2-D	500[2]
31[3]	SLM	Color	1/2.5	1000	609.6 mm, f6	None	None	2-D	500
35	Hg	Color	1/2.5	1000	609.6 mm, f6	None	SLM @90°[5] P.F. @45°	Blue & Red Filter Matrix	500
37	Hg	Color	1/2.5	3000	203 mm, f7.7	None	P.F. @45°	B&R Filter Matrix	500
38	Hg	Color	1/2.5	5000	203 mm, f7.7	None	P.F. @45°	B&R Filter Matrix	500
39	Hg	Color	1/2.5	5000	203 mm, f7.7	None	P.F. @45°	B&R Filter Matrix	800
41	Hg	Color	1/2.5	5000	203 mm, f7.7	None	P.F. @45°	B&R Filter Matrix	200
42	None	Color	1/2.5	5000	203 mm, f7.7	None	SLM @90° P.F. @45°	None	500
43	Hg	Color	1/2.5	5000	203 mm, f7.7	None	P.F. @45°	Blue & Red Filter Matrix	50
44	None	Color	1/2.5	5000	203 mm, f7.7	None	SLM @90° P.F. @45°	None	800
45	None	Color	1/2.5	5000	203 mm, f7.7	None	SLM @90° P.F. @45°	None	200
46	None	Color	1/2.5	5000	203 mm, f7.7	None	SLM @90° P.F. @45°	None	50
47[4]	None	Color	1/2.5	5000	203 mm, f7.7	None	SLM @90° P.F. @45°	None	500

TABLE III (Footnotes)

1. Color film was Kodak ektachrome 7241, black and white was Kodak 4-X reversal film.

2. After No. 29 Pressure was read from a dome loader, prior to No. 29 it had been taken from a tapped plug installed in the 45° window.

3. The two small windows on the optical axis (formerly plastic) were replaced by Pyrex which was used from No. 31 on.

4. All listed runs except No. 47 had sample orientation such that the binder was aligned with the optical axis. No. 47 was intentionally cocked to show both the edge and a face of the propellant sandwich.

5. SLM refers to the SLM-1200 projector, P.F. refers to the television photo flood.

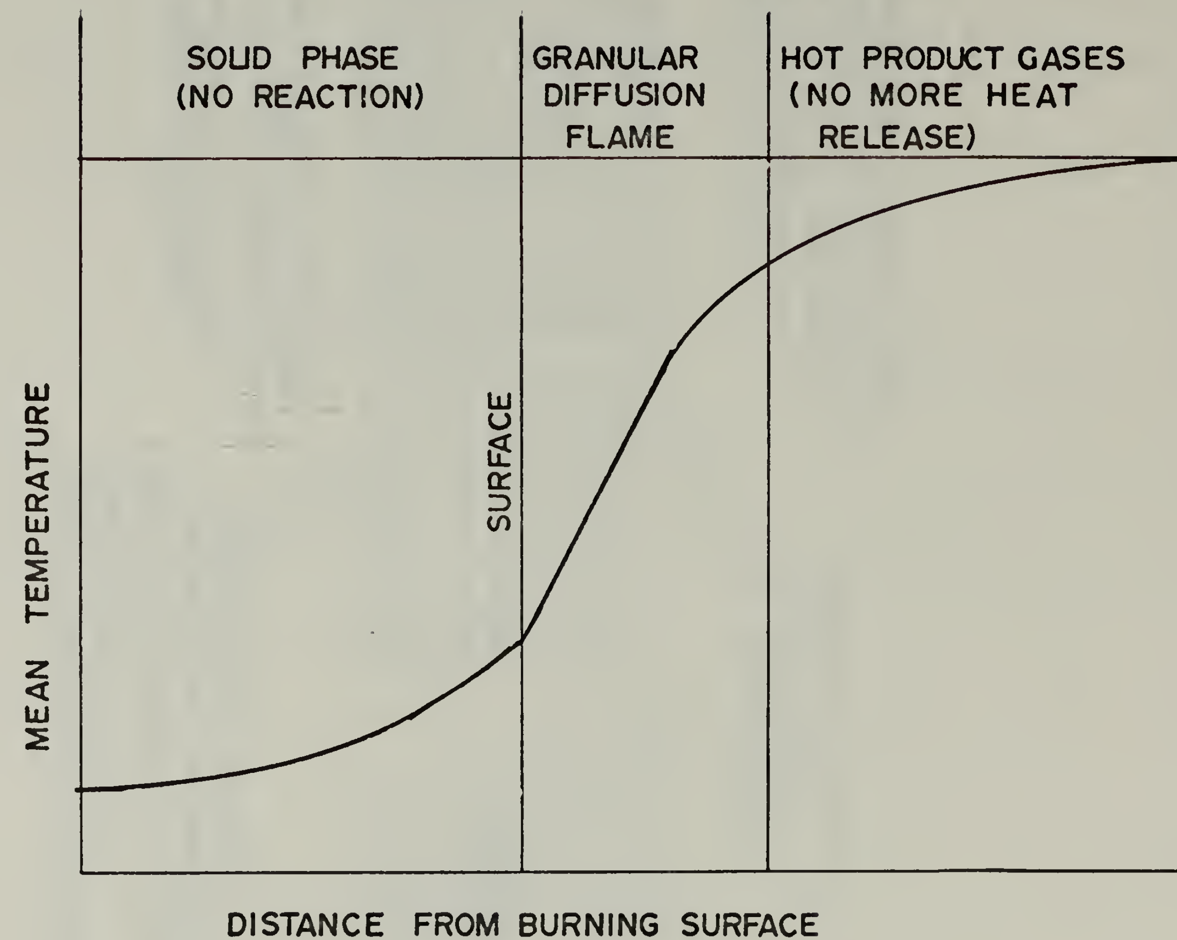


FIGURE 1. GRANULAR DIFFUSION FLAME MODEL [Ref. 4]

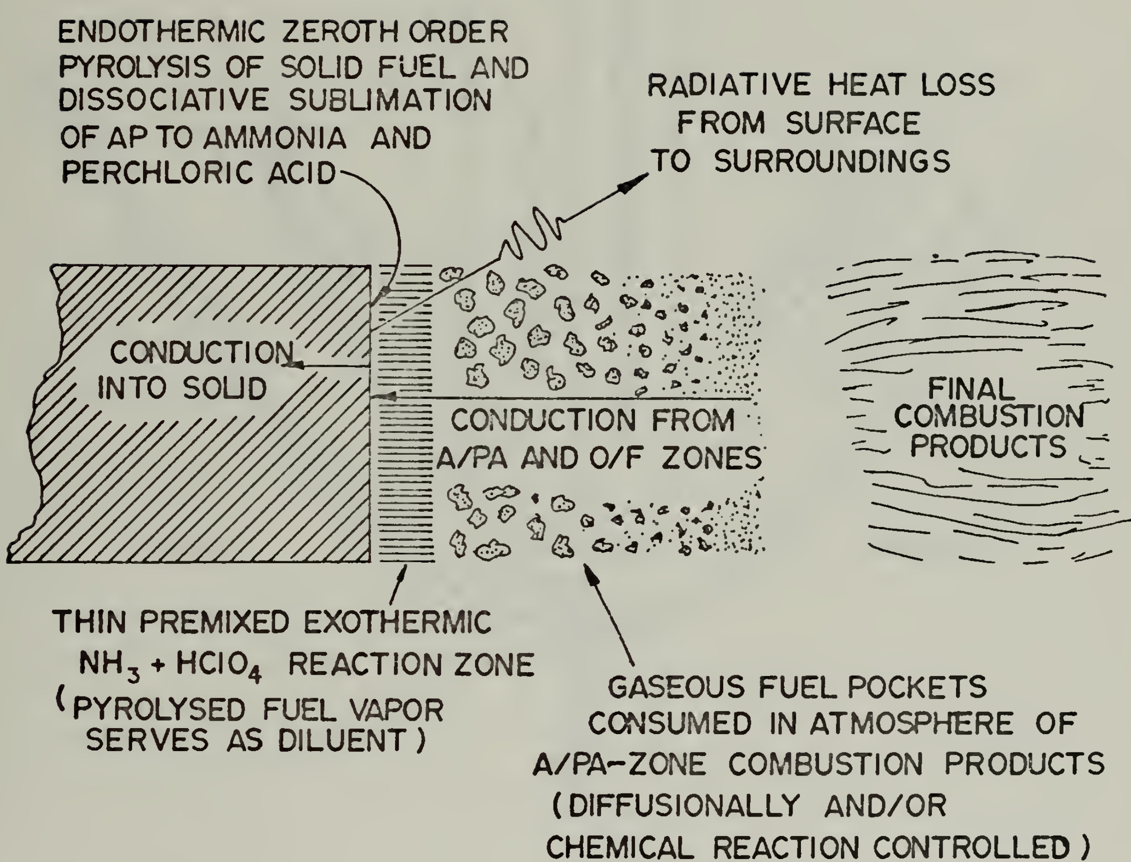


FIGURE 2. MODIFIED GRANULAR DIFFUSION FLAME MODEL [Ref. 5]

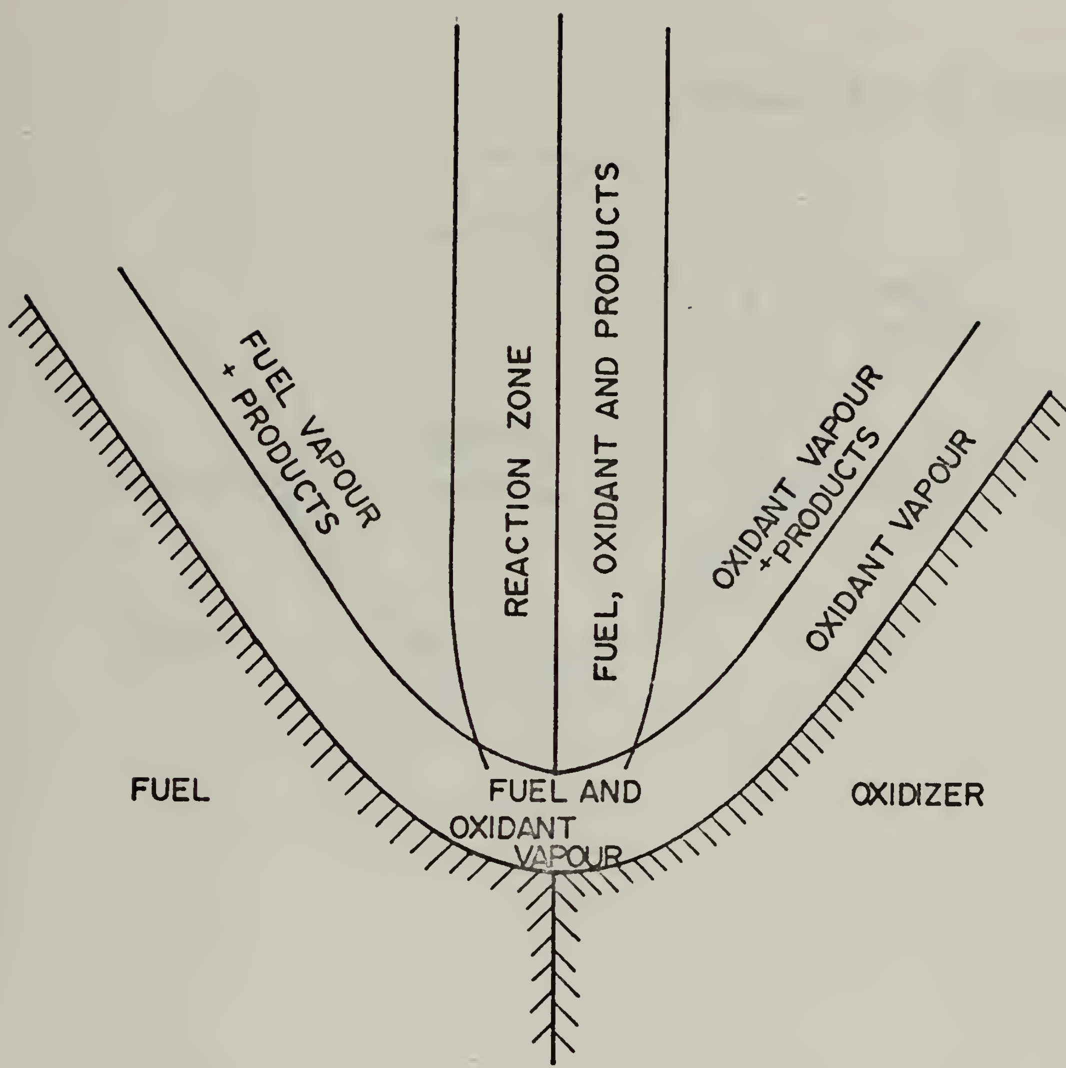


FIGURE 3. PHALANX FLAME MODEL (Fig. 4 of Ref. 6)

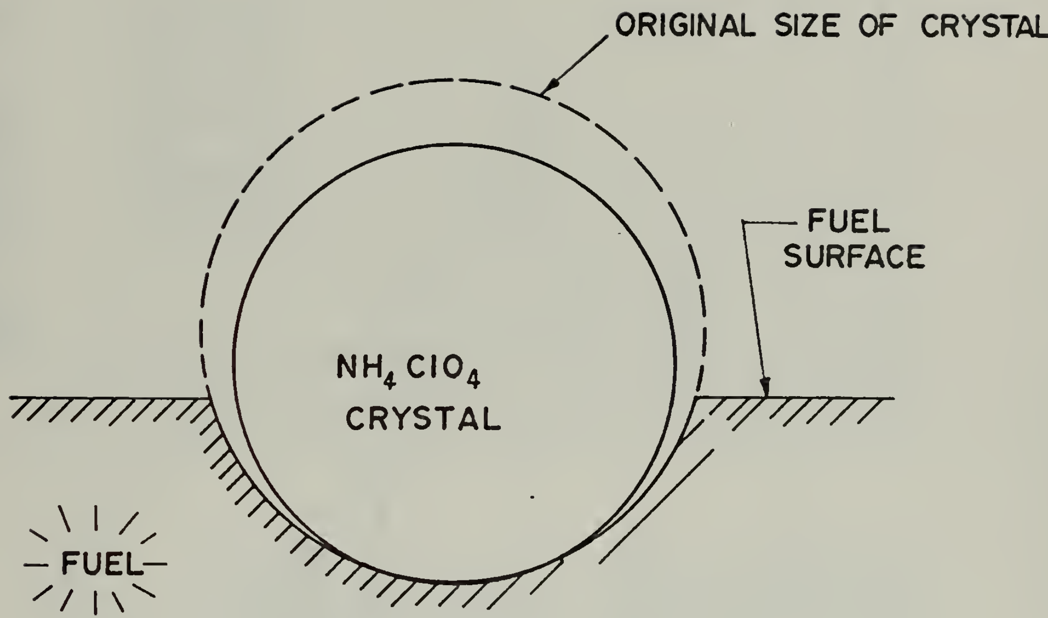


FIGURE 4. HETEROGENEOUS REACTION MODEL (Fig. 1 of Ref. 7)

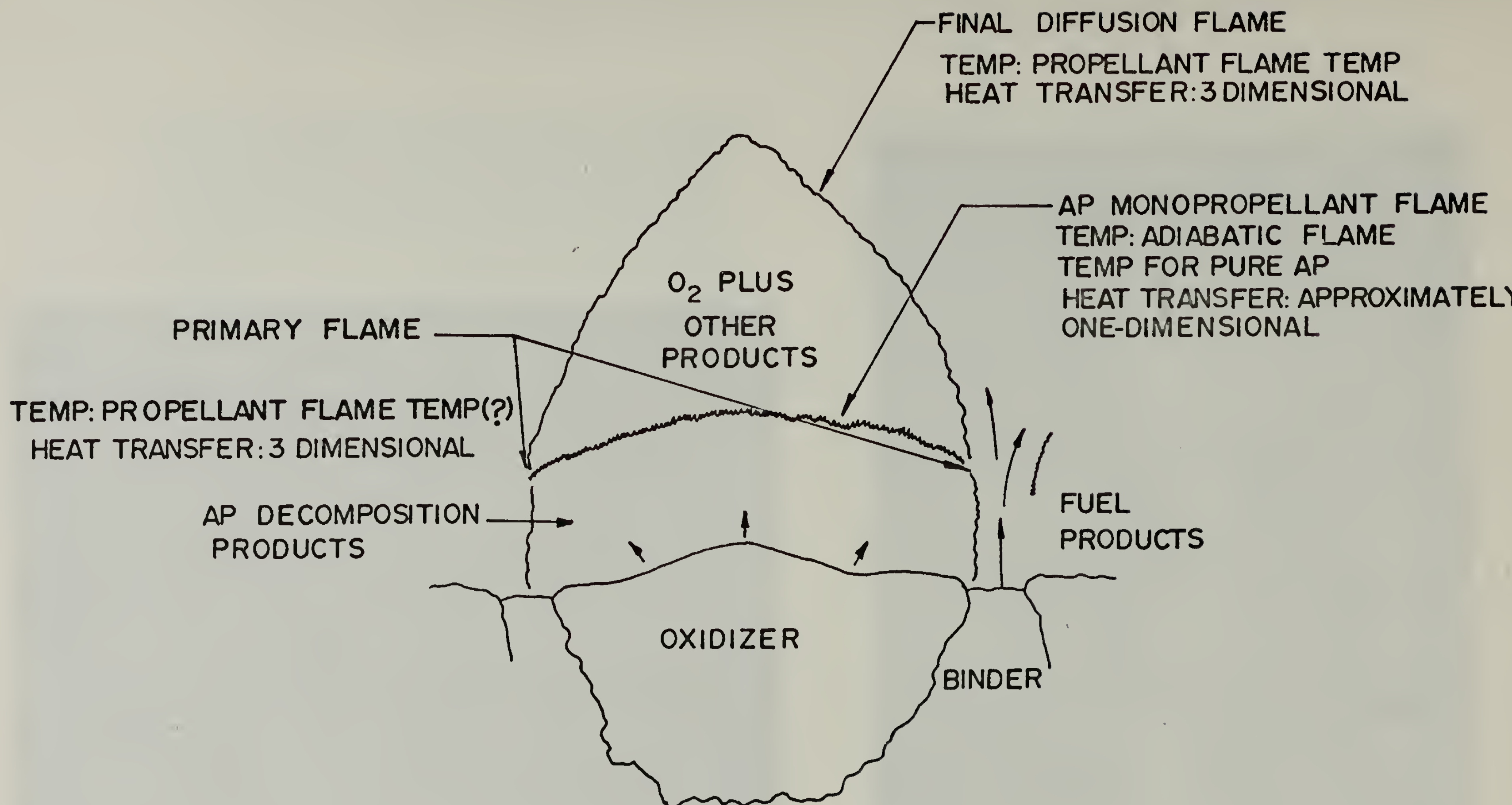


FIGURE 5. MULTIPLE FLAME MODEL (Fig. 1 of Ref. 9)

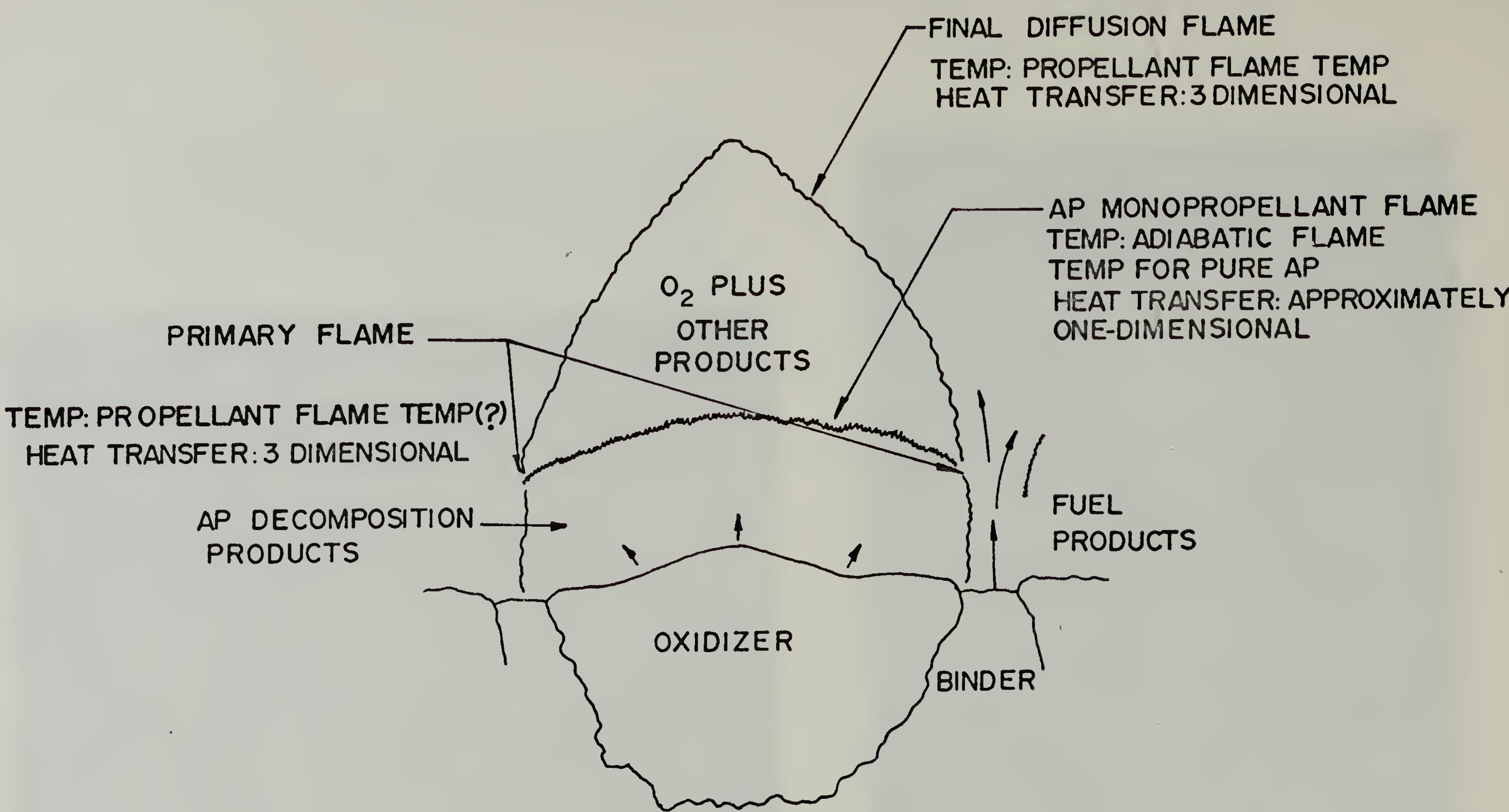


FIGURE 5. MULTIPLE FLAME MODEL (Fig. 1 of Ref. 9)

FIGURE 6. View of Center Section showing base and two window locations (one large, one small)

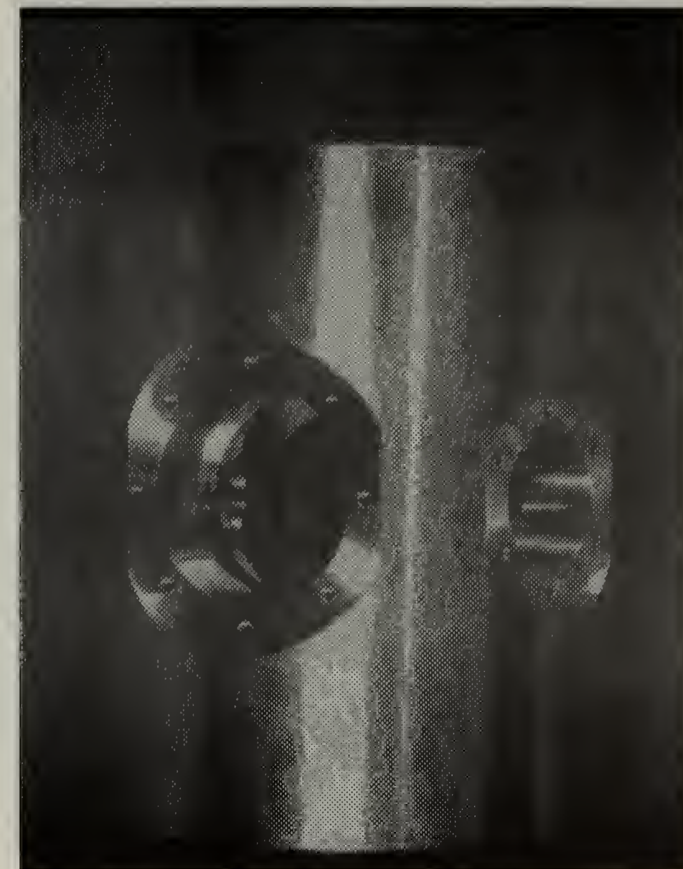


FIGURE 7. Frontal View of Center Section

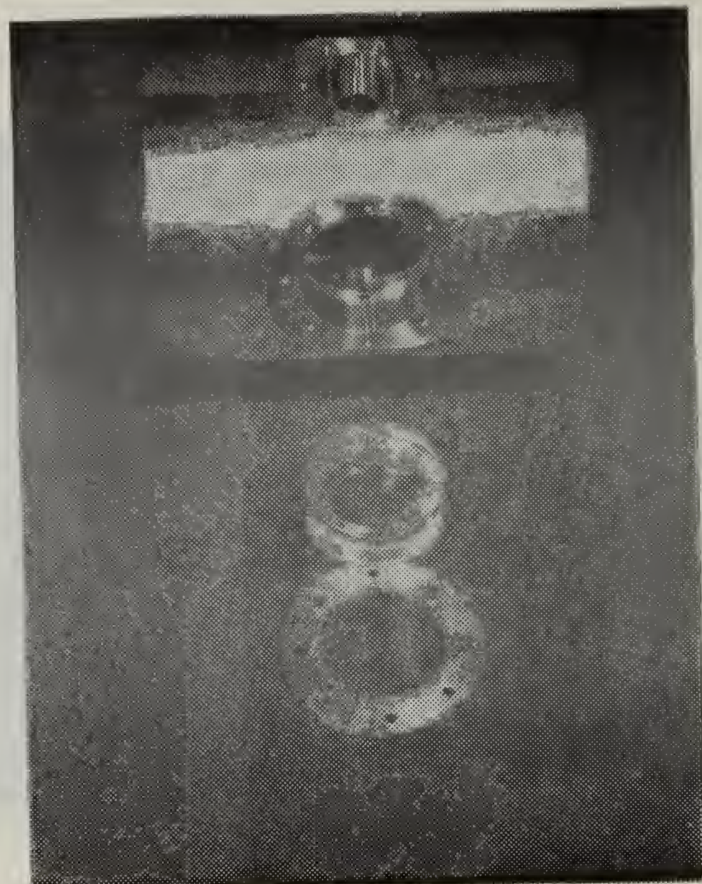


FIGURE 8. Exploded View of Large Window

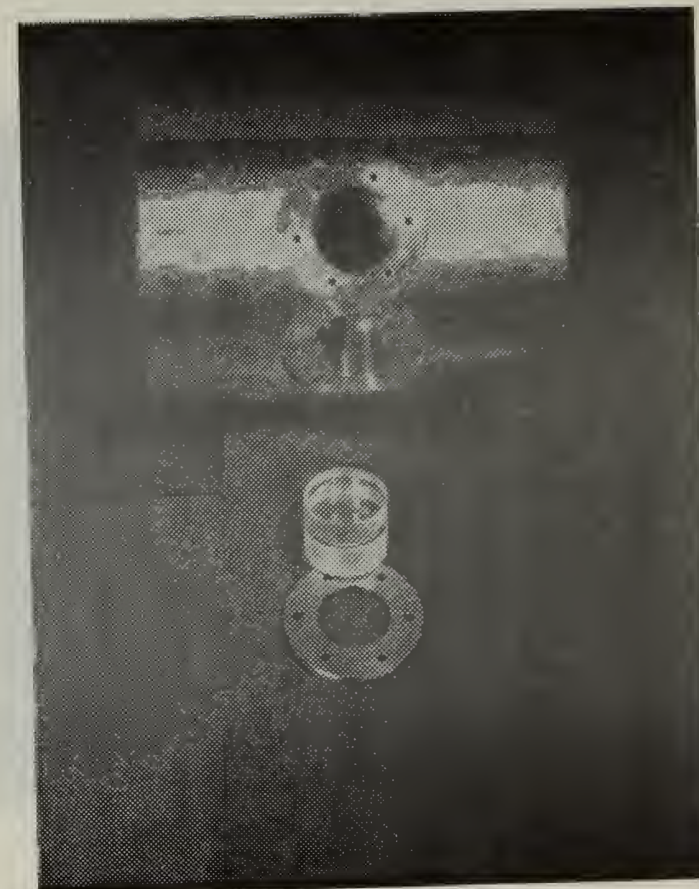


FIGURE 9. Exploded View of Small Window

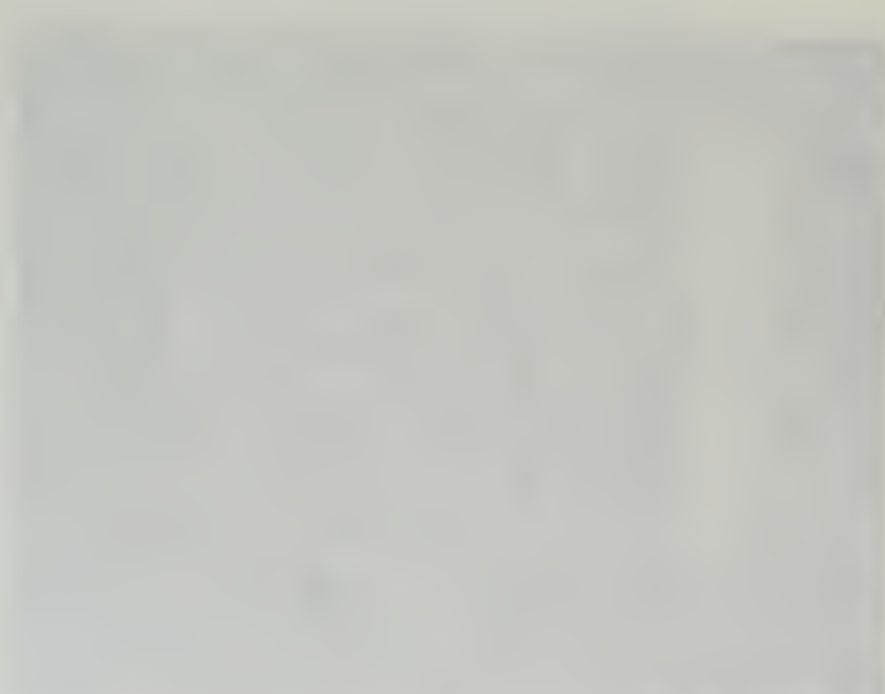


FIGURE 10. View of Center Section showing the top and the same two windows as Fig. 6

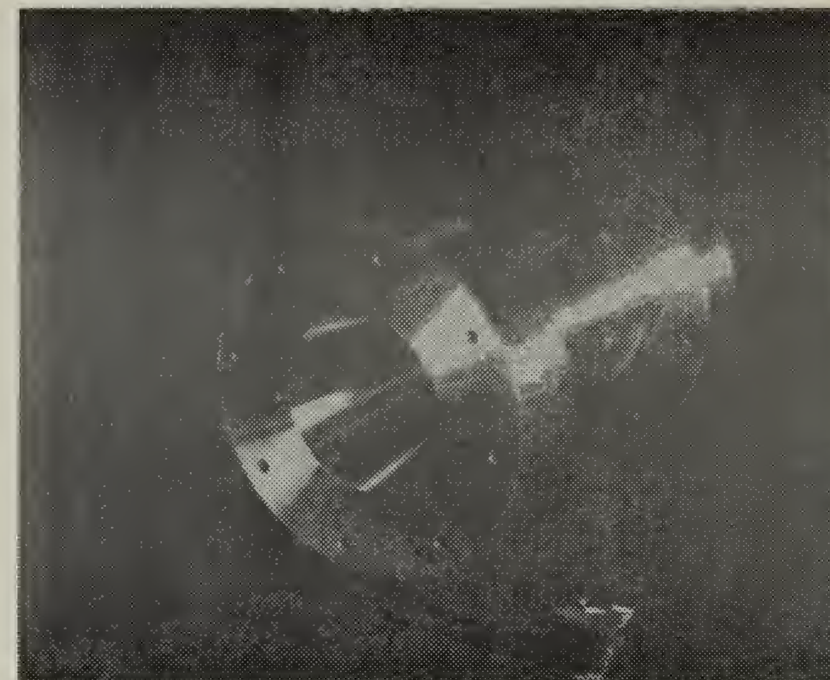


FIGURE 11. View of Exhaust Section showing the bottom and two of the four exhaust line holes

FIGURE 12. View of Exhaust Section showing "O" ring groove on top, large opening for later addition of rupture diaphragms (covered by 3/8" steel plate for this study)

FIGURE 13. View of Bottom Section showing top and mounting locations for primary and secondary diffusion plates (marked with flagged arrows A & B respectively)

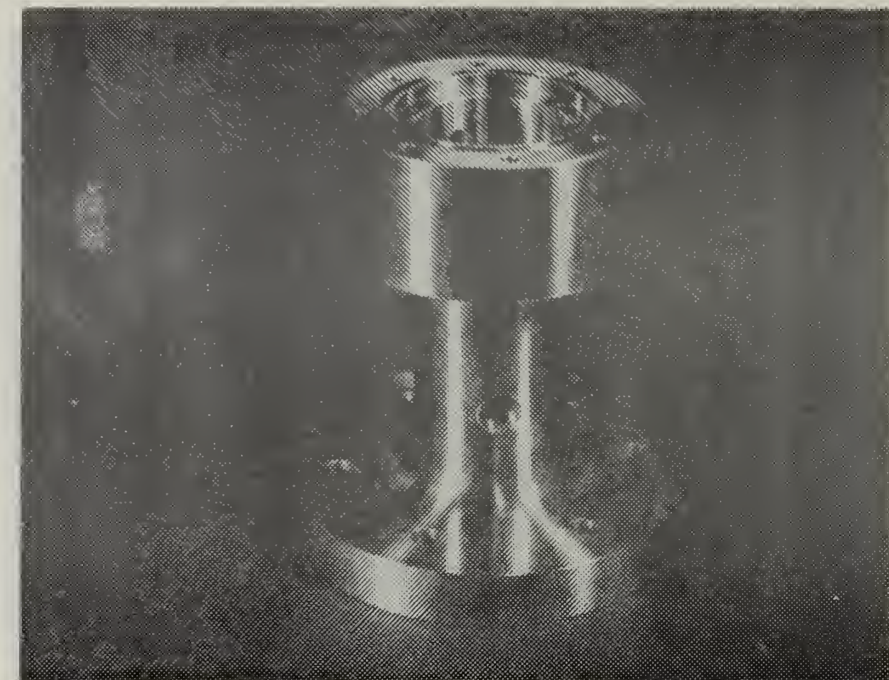


FIGURE 14. Frontal View of Base Section showing N_2 purge inlet

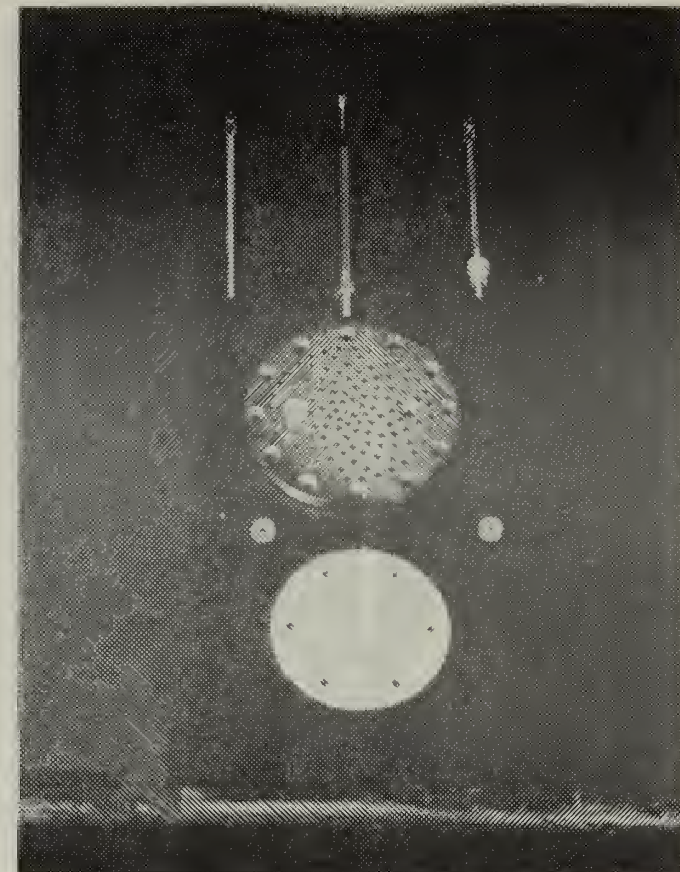


FIGURE 15. Exploded View of Primary diffusion plate, insulating washers, secondary diffusion plate, ignition posts and propellant stand and pedestal

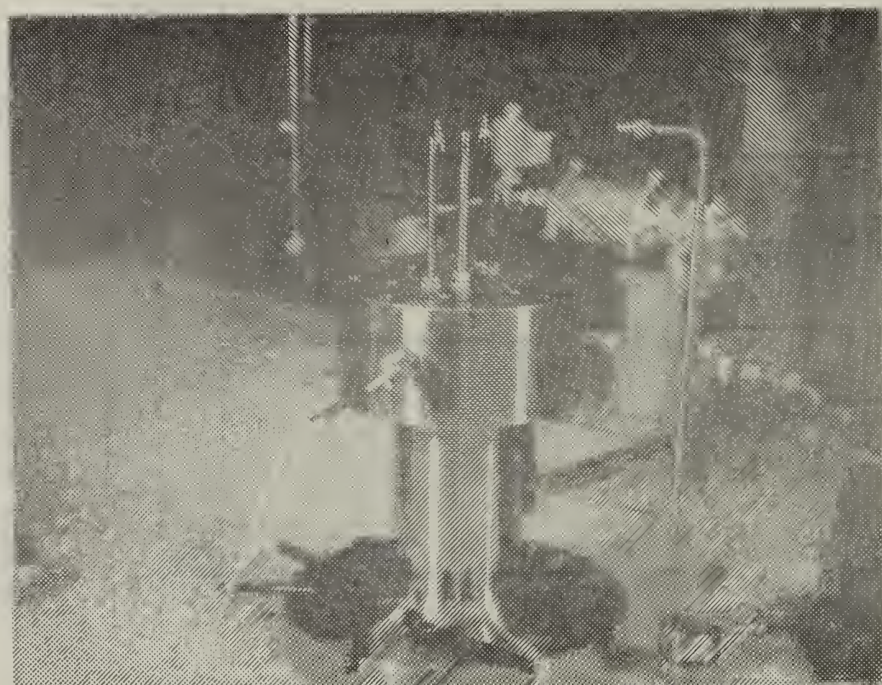


FIGURE 16. View of Assembled Base Section showing electrical lead-ins for ignition

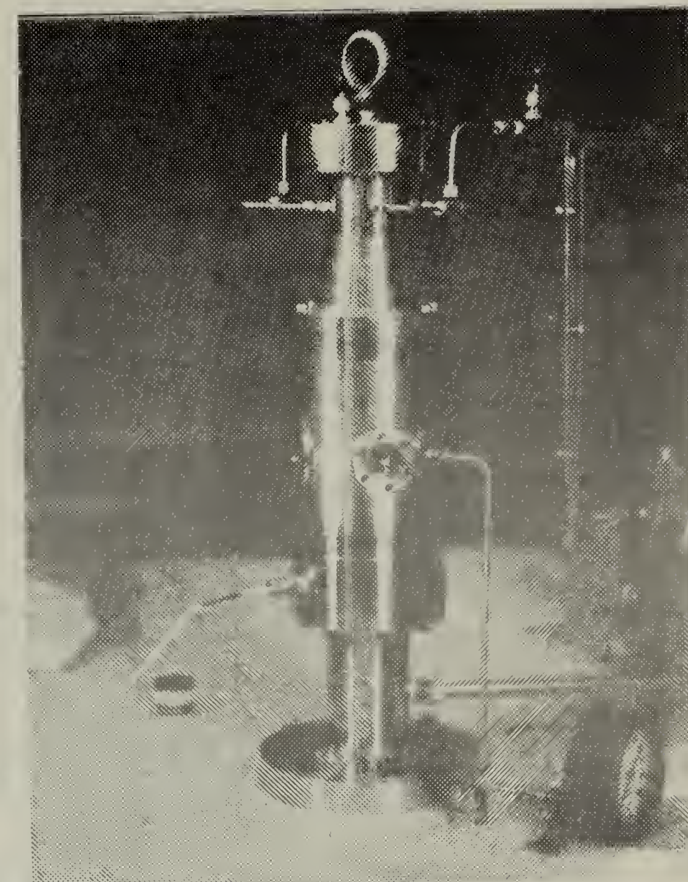


FIGURE 17. View of Assembled Combustion Bomb along the optical axis showing pressure tap installed in a window plug and lifting ring

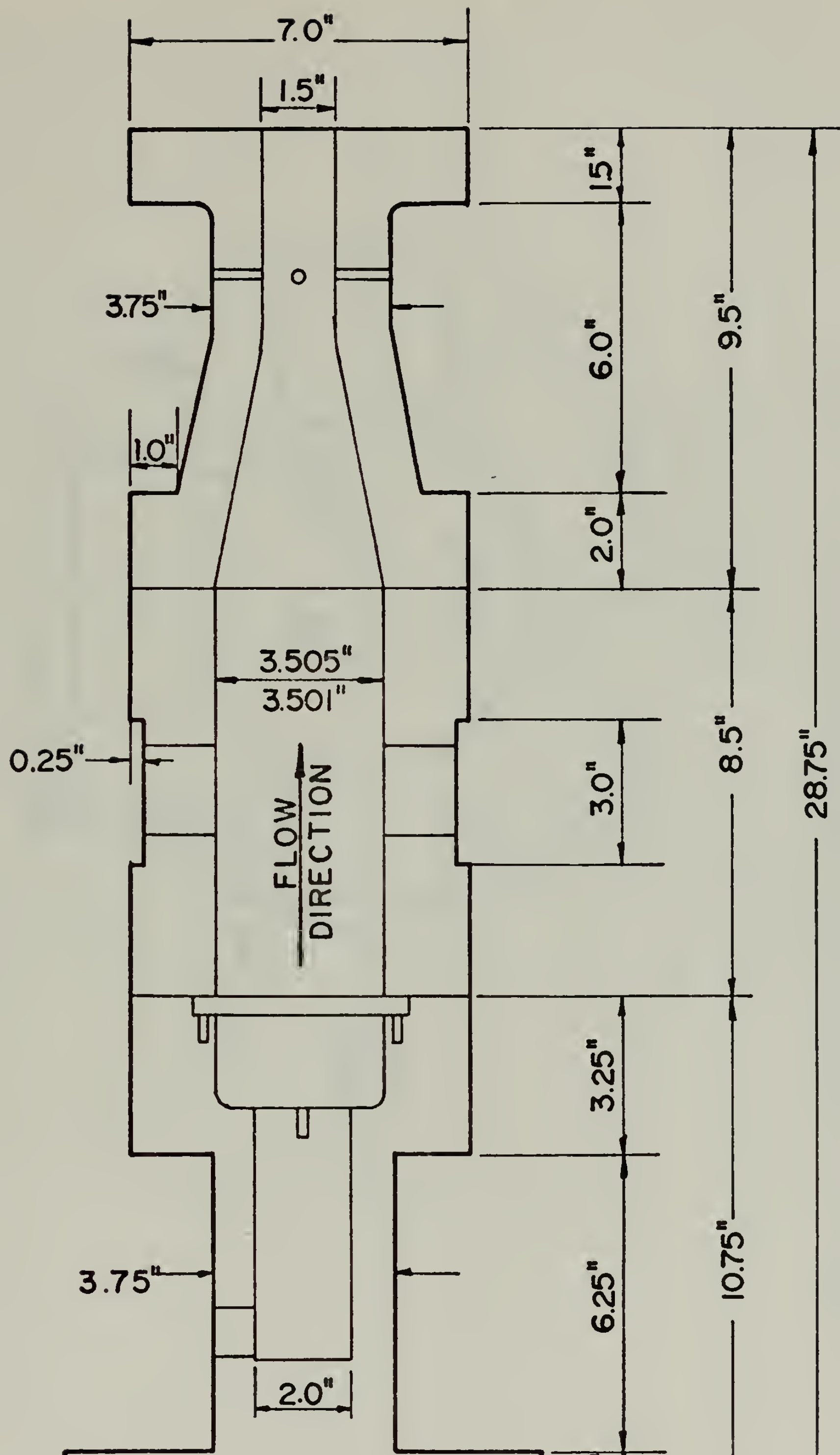


FIGURE 18. SCHEMATIC OF COMBUSTION BOMB SHOWING PRINCIPAL DIMENSIONS

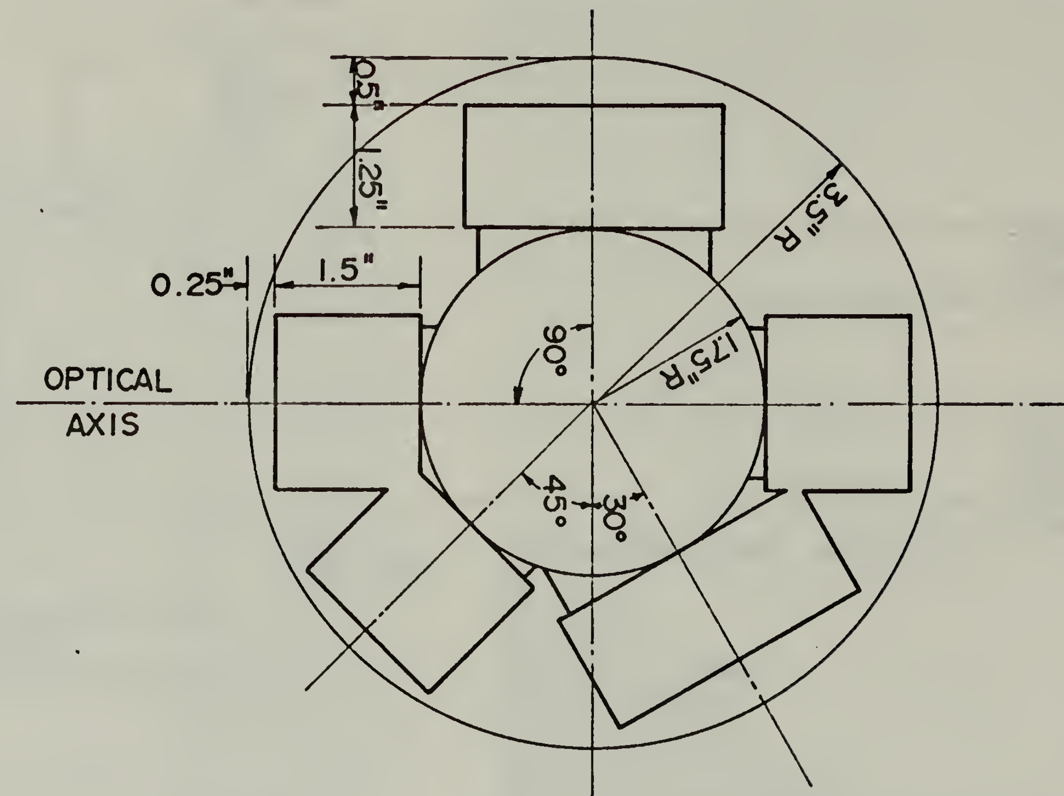


FIGURE 19. SCHEMATIC SHOWING ANGULAR RELATIONSHIP OF WINDOWS

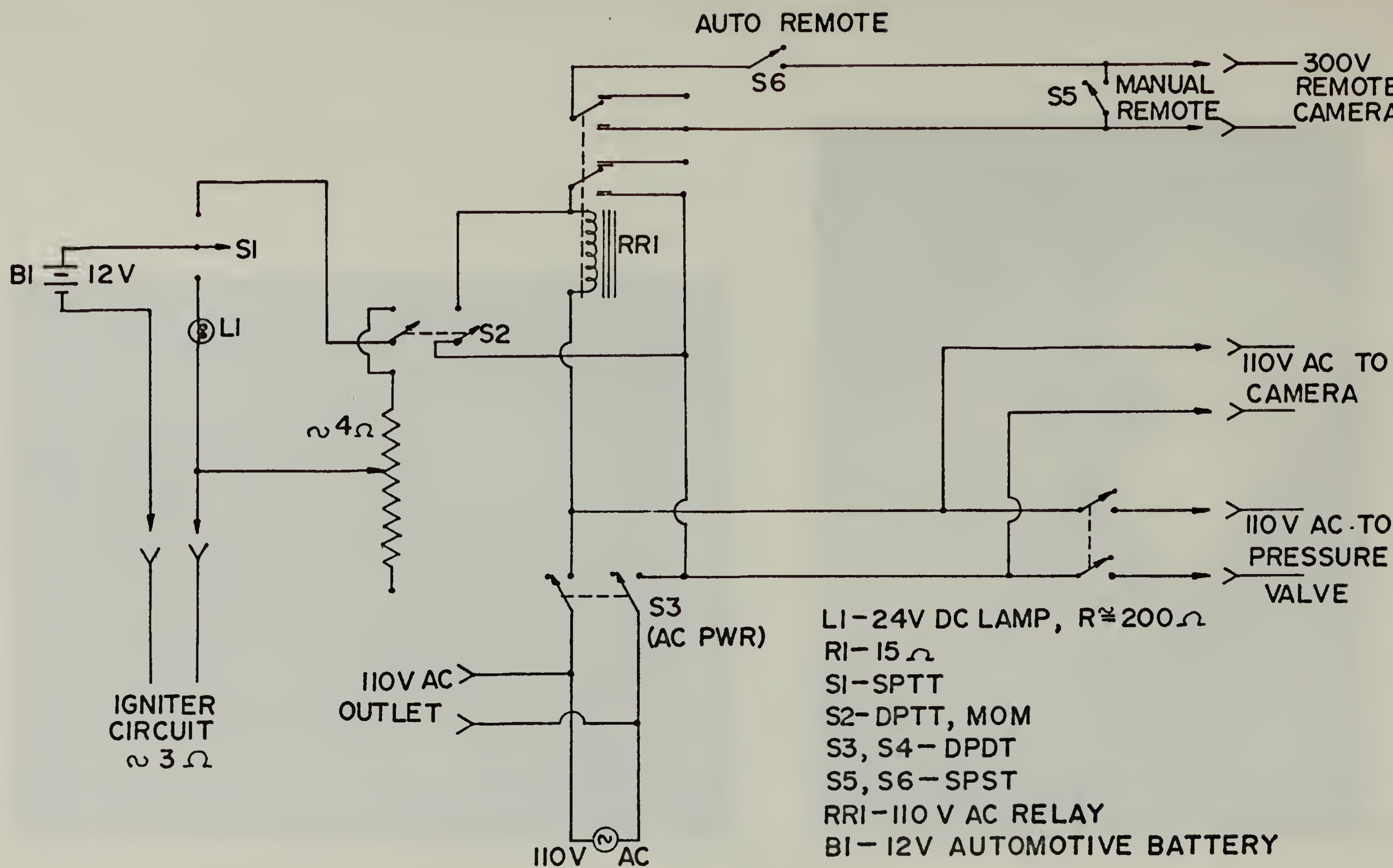


FIGURE 20. ELECTRICAL SCHEMATIC OF CONTROL PANEL

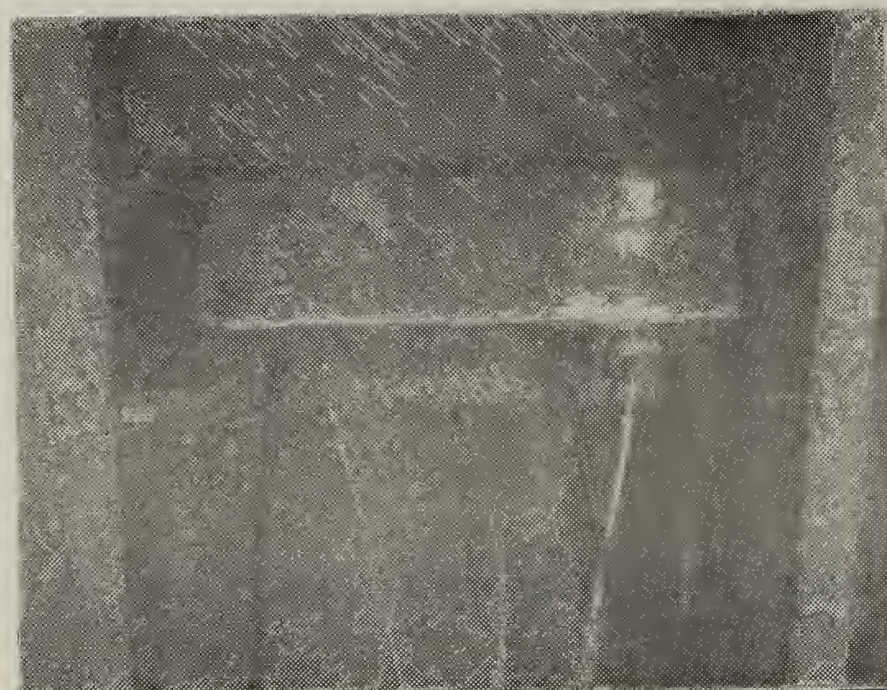


FIGURE 21. Electrical Control Panel

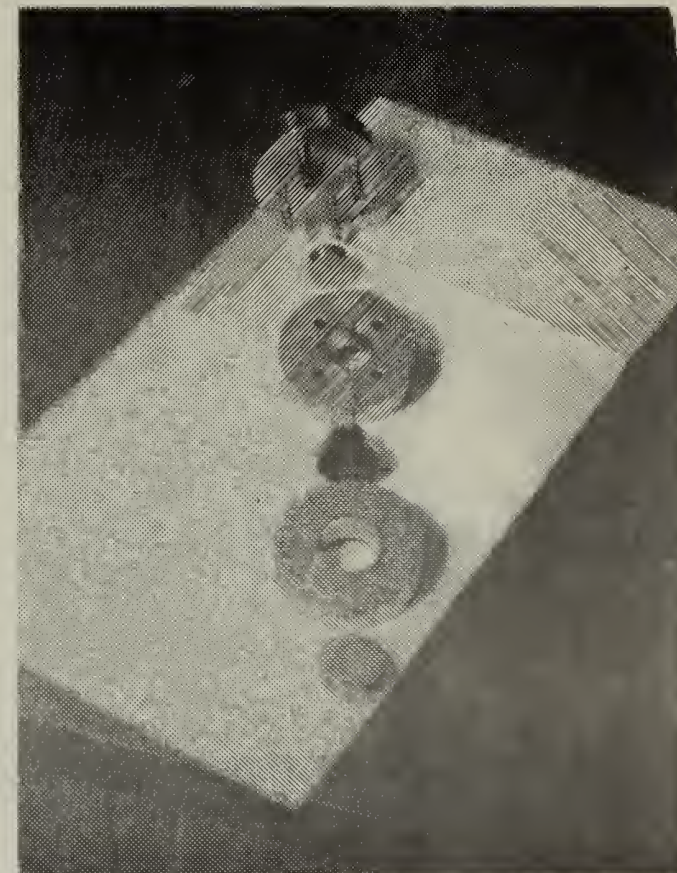
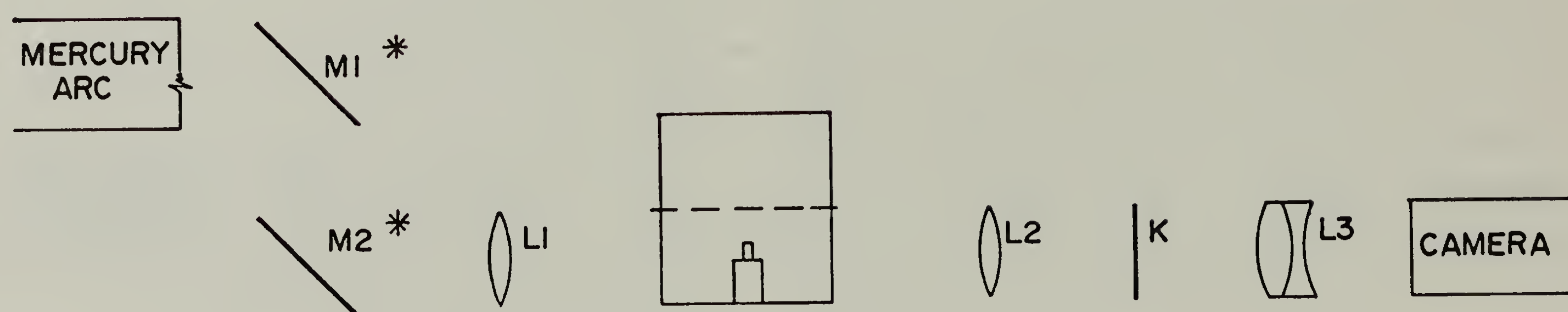


FIGURE 22. Exploded View of one inch compaction mold

M1 – 1st SURFACE MIRROR
M2 – 1st SURFACE MIRROR
L1 – 1st SCHLIEREN LENS
L2 – 2nd SCHLIEREN LENS
L3 – CAMERA FOCUS LENS
K – KNIFE EDGE



* 1st SURFACE MIRRORS REQUIRED BECAUSE OF FIXED HEIGHT OF MERCURY ARC.

FIGURE 23. SCHEMATIC OF ONE-DIMENSIONAL SCHLIEREN OPTICS

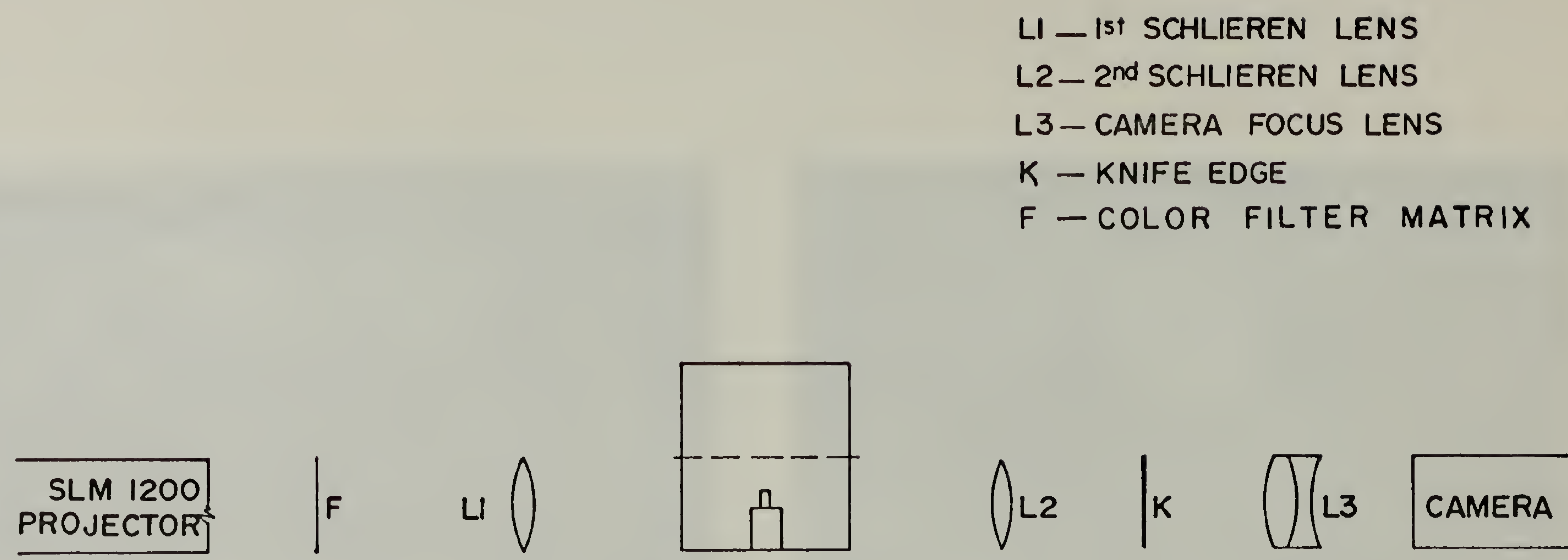


FIGURE 24. SCHEMATIC OF TWO-DIMENSIONAL SCHLIEREN OPTICS

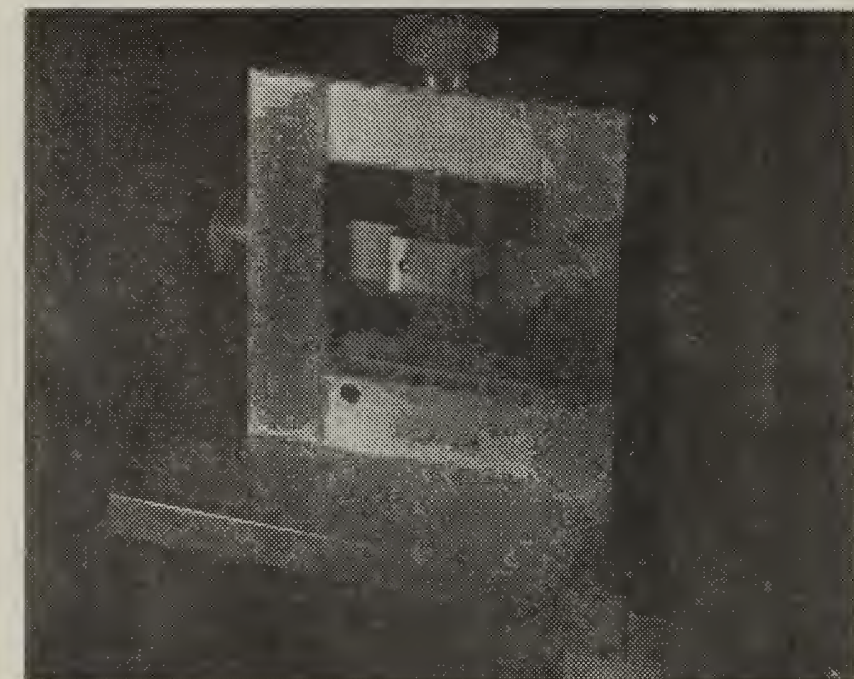


FIGURE 25. Two-Dimensional Schlieren Knife Edge

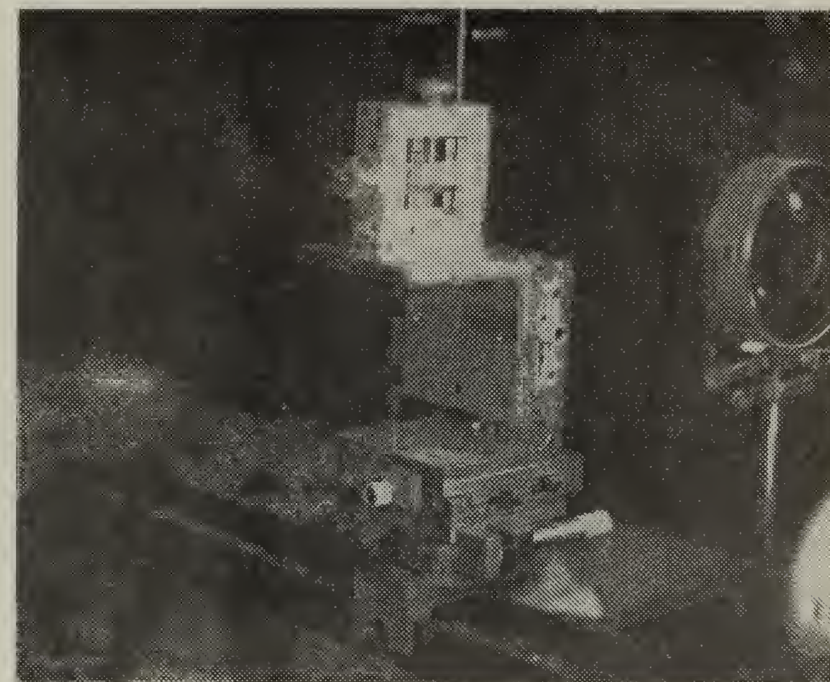


FIGURE 26. Two-Dimensional Knife Edge on Translation Stages

FIGURE 27. Photograph at 800 psi from film No. 44

FIGURE 28. Schlieren photograph at 800 psi from film No. 39

FIGURE 29. Photograph at 500 psi from film No. 42

FIGURE 30. Schlieren photograph at 500 psi from film No. 38

FIGURE 31. Photograph at 200 psi from film No. 45

FIGURE 32. Schlieren photograph at 200 psi from film No. 41

FIGURE 33. Photograph at 50 psi from film No. 46

FIGURE 34. Schlieren photograph at 50 psi from film No. 43

FIGURE 35. Off-axis photograph at 500 psi from film No. 47

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13. ABSTRACT

Ammonium perchlorate/polybutadiene acrylic acid propellant sandwiches were burned in a nitrogen purge atmosphere at various pressures in a combustion bomb designed for optical and rapid de-pressurization studies. A Hycam camera was utilized for taking high speed color schlieren and regular photographs to obtain information about the flame structure during combustion. The effects of pressure on flame structure are discussed.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
solid propellant combustion						
schlieren						
ammonium perchlorate						
sandwich burning						

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c.1 An optical study of ammonium perchlorate sandwiches with a poly-butadiene acrylic acid binder.